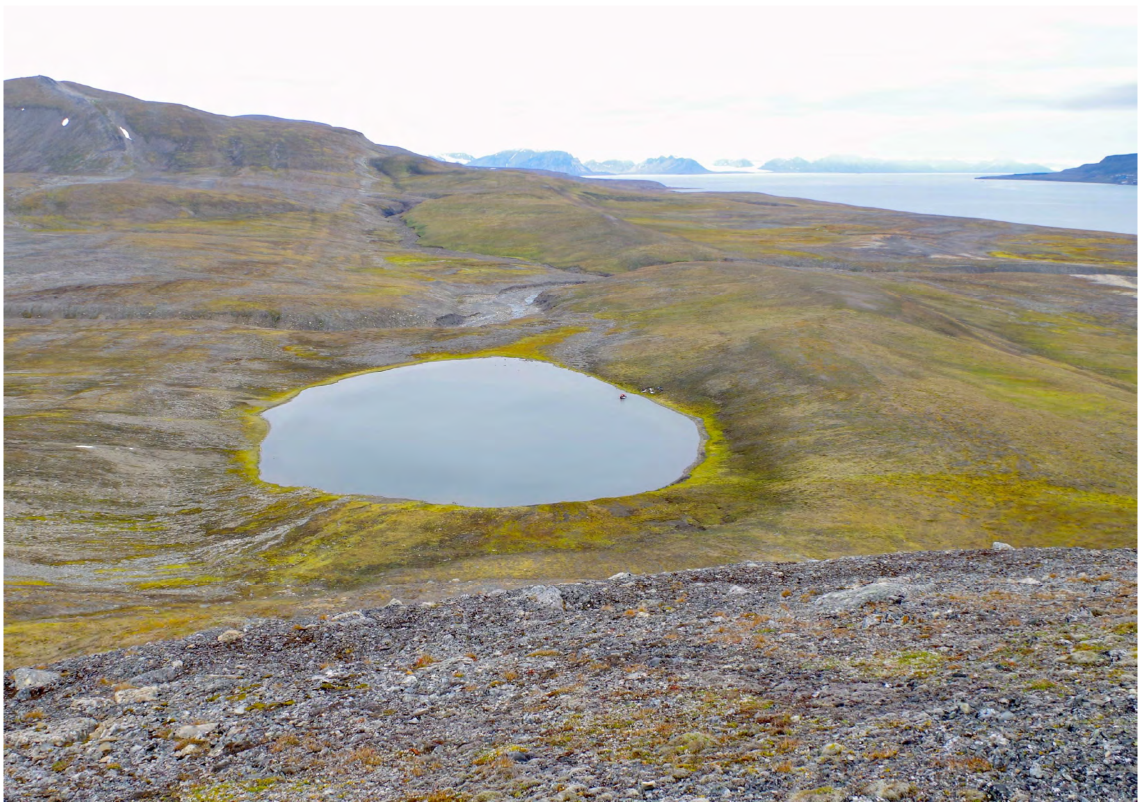
Past Precipitation on Svalbard 2



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Past Precipitation on Svalbard
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Heftyevatnet, western Spitsbergen, August 9, 2017. View towards north. Small boat platform used for sediment coring is returning to the eastern shore of the lake.

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Abstract

The Svalbard archipelago is experiencing dramatic effects of climate change. Rising temperatures cause glaciers to retreat and thin, sea-ice cover to decline, and have direct consequences for the settlements. Residential areas and infrastructure are threatened by thawing permafrost and increased frequency of slope processes such as mudslides, debris flows, and avalanches. A key factor for these changes is the changing precipitation regime, with more precipitation falling as rain rather than snow, and more frequent and intense heavy precipitation events. In this project, we use the hydrogen isotopic composition of leaf waxes (δ^2H_{wax}) to reconstruct precipitation variability throughout the Holocene (the last *c*. 11,700 years). This allows us to examine the natural precipitation variability and to place recent changes into a long-term context. 'Past Precipitation on Svalbard 2' is a continuation of an earlier project supported by the Svalbard Environmental Protection Fund (project number 17/101). Here, we improve the temporal resolution of the isotope record from Heftyevatnet and add a high-resolution record from Linnévatnet. The Heftyevatnet record suggests a trend towards drier summer conditions and higher evapotranspiration during the Early and Middle Holocene, followed by cooler and wetter summers the last *c*. 6 thousand years. The isotopic composition of the Linnévatnet samples has not yet been measured but will be compared to observational meteorological data from the last *c*. 60 years to examine how δ^2H_{wax} correlates to seasonal precipitation variability.

Introduction

Due to its location at the end of the North Atlantic cyclone track and influence of warm Atlantic water currents, Svalbard experiences exceptionally warm and wet conditions for its high latitude (Førland et al., 2009). In the latest decades, Svalbard has experienced amplified warming, increased annual precipitation amounts, and more frequent and extreme precipitation events (Hanssen-Bauer et al., 2019; Førland et al., 2020; Nordli et al., 2020). The increases in (extreme) precipitation have been associated with sea-ice decline (Müller et al., 2022), extreme cyclone events over the Barents Sea and increased atmospheric flow of southerly Atlantic moisture (Serreze et al., 2015). Extreme precipitation poses a threat to ecosystems and infrastructure by resulting in e.g., avalanches, landslides, and flooding followed by ground freezing (Larsson, 1982; Hansen et al., 2014).

In light of the modern climate trends, there is an urgent need for increased knowledge and understanding of past climate variability. A number of 50-100-yr long precipitation records are available from Svalbard (Førland et al., 2020 and references therein), but longer records are needed to assess the full range of natural variability. 'Past Precipitation on Svalbard 2' (PPS2) is a continuation of 'Past Precipitation on Svalbard' (PPS; project number 17/101), aiming to reconstruct Holocene precipitation seasonality on Svalbard (Schomacker & Kjellman, 2021). The Holocene is the current geological period, spanning the last *c*. 11,700 years, i.e., the time since the end of the last ice age. This is a period generally characterized by relatively stable climate, but as the Early Holocene was warmer than today, it might serve as an analogue to future warmer climate. Studying precipitation changes during this warm period in relation to the rest of the Holocene can therefore help us understand how and why Arctic precipitation patterns vary with changing atmospheric conditions.

PPS and PPS2 are based on analyses of lipid biomarkers preserved in lake sediments. Biomarkers are organic molecules that indirectly record past environmental and climate conditions. One type of biomarker is waxes produced by plants to protect their leaves and keep their moisture balance. These leaf waxes consist of long hydrocarbon chains that are persistent to degradation over long geological timescales (Eglinton & Eglinton, 2008). The stable isotopic composition of hydrogen in the leaf waxes (δ^2H_{wax}) is highly correlated to the isotopic composition of the source water used by the plant (Sachse et al., 2012; McFarlin et al., 2019). They are therefore a powerful tool for paleoclimatologists studying climates of the past. Depending on the lake and catchment characteristics, δ^2H_{wax} may allow us to explore seasonal differences in precipitation, i.e., whether changes occurred in summer or winter. This information is very valuable since the seasonality of the precipitation changes have implications for e.g., glacier mass-balance changes and can be linked to winter sea-ice variability (Bintanja & Selten, 2014; Thomas et al., 2016, Müller et al., 2022). Furthermore, Arctic precipitation changes can result from moisture source changes in summer, with great moisture transport from lower latitudes resulting in precipitation increases (Vázquez et al., 2016; Bintanja et al., 2020).

In PPS, a pilot study was conducted on northern Svalbard (Kjellman et al., 2020), and additional analyses were performed on material from lakes along a southwest-northeast oriented climatic transect (Fig. 1A). The lakes were chosen based on location and precipitation seasonality reflected in the lake water isotopes. We analyzed leaf wax compounds (fatty acids) of different chain lengths to decipher seasonal trends in precipitation. The main aim of PPS2

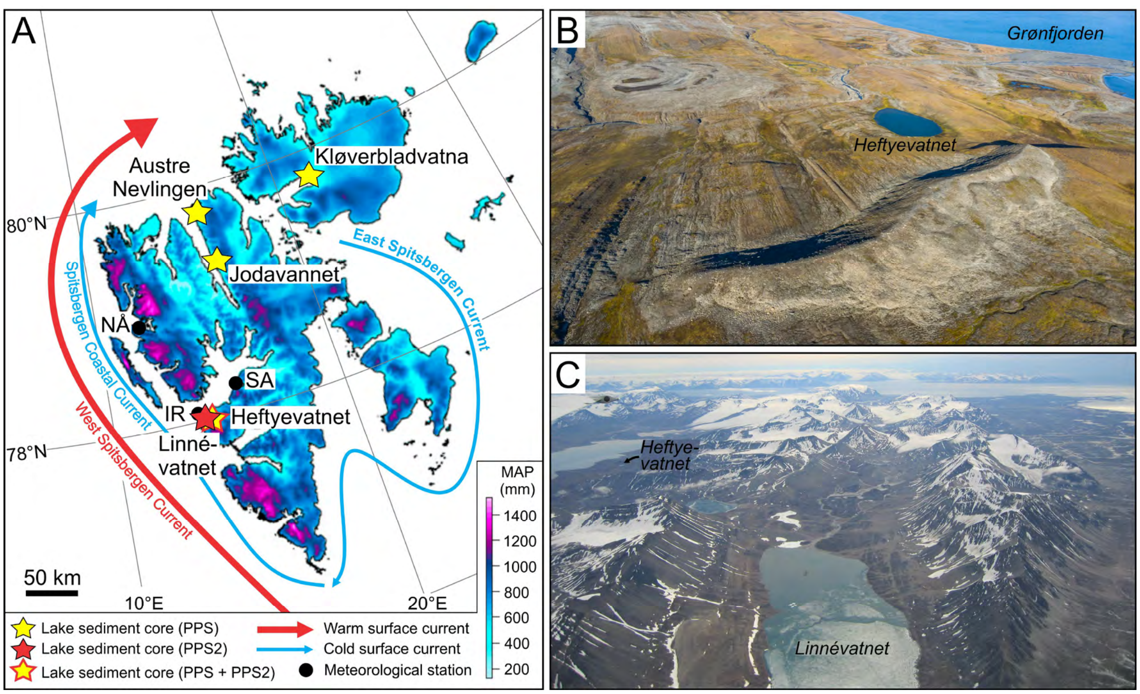

Fig. 1. (A) Map of Svalbard, showing study locations for projects PPS, PPS2 and meteorological stations (IR = Isfjord Radio; NÅ = Ny-Ålesund; SA = Svalbard Airport). Background map with modeled mean annual precipitation (MAP; mm) for the period 1971-2000 from Førland et al. (2020). (B) Heftyevatnet, western Spitsbergen (view towards north). (C) Linnévatnet, western Spitsbergen (view towards south). Heftyevatnet is visible in the background. Photograph: E. S. Mannerfelt (B) and A. Schomacker (C).

is to enhance the temporal and spatial resolution of records. More specifically, the aim is to add more samples to the Heftyevatnet record generated in PPS (increased temporal resolution) and analyze samples from one new lake, Linnévatnet (increased spatial resolution). The two lakes are located close to the west coast of Spitsbergen, which receives relatively high mean annual precipitation amounts (Førland et al., 2020; Fig. 1A).

The lake and catchment characteristics have important implications for the leaf wax interpretations by influencing the seasonality reflected in the terrestrial (long-chained, C_{28}) and aquatic (mid-chained, C_{22}) δ^2H_{wax}. Terrestrial waxes (δ^2H_{terr}) are often assumed to reflect summer precipitation δ^2H, since the soil water used by the terrestrial plants is mostly recharged by summer precipitation (Cooper et al., 1991; Throckmorton et al., 2016). Aquatic waxes (δ^2H_{aq}), on the other hand, can reflect different seasonality depending on how often the water in the lake is replaced (Cluett & Thomas, 2020; Thomas et al., 2020). The aquatic plants can either use water originating from summer precipitation (in lakes with short lake water residence time) or a mix of precipitation from all seasons (in lakes with long residence times). Furthermore, the abundance of aquatic leaf waxes partly depends on the growth conditions in the lake. High amounts of suspended material in the lake can block out sunlight needed by plants to grow. On Svalbard, there are almost no aquatic vascular plants, but submerged aquatic mosses are abundant in some lakes (e.g., Balascio et al., 2018; Kjellman et al., 2020).

Heftyevatnet is a small lake *c*. 700 m onshore from Grønfjorden with a relatively large catchment-to-lake ratio, no glacial meltwater inflow, and no active inlet or outlet (Fig. 1B). Because of the large catchment-to-lake ratio, and relatively high precipitation amounts, Heftyevatnet is likely flushed by spring melt, and by rain throughout summer. Therefore, both terrestrial (C_{28}) and aquatic (C_{22}) δ^2H_{wax} are likely reflecting summer precipitation δ^2H. The difference between the two (ε_{28-22}) can be used to infer changes in summer evaporative enrichment of terrestrial leaf water (Rach et al., 2017). Linnévatnet is a proglacial lake in Linnédalen, 7 km northwest of Heftyevatnet (Fig. 1C). The lake receives inflow from the glacier-fed river Linnéelva and is characterized by minerogenic deposition and low organic production. Hence, we focus on the long-chained terrestrial waxes in Linnévatnet, reflecting summer precipitation δ^2H, since the abundance of aquatic mosses is presumably low.

Methods

To reconstruct past precipitation changes, we measured the hydrogen isotopic composition of leaf wax compounds (δ^2H_{wax}) extracted from the lake sediments. In PPS, we analyzed sediments from four lake records across Svalbard (Fig. 1A) to capture differences between the relatively humid west coast (Heftyevatnet) and the more arid central and northern parts of Svalbard (Jodavannet, Austre Nevlingen, and Kløverbladvatna). In PPS2, the Heftyevatnet record was complemented with six new samples to fill gaps in the leaf wax record. The lower part of this sediment record has previously been analyzed to reconstruct postglacial glacioisostatic rebound and deglaciation history (Farnsworth et al., 2022). Additionally, sediment samples were collected from Linnévatnet, 7 km northwest of Heftyevatnet. Linnévatnet is a well-studied proglacial lake (e.g., Svendsen et al., 1987; Mangerud & Svendsen, 1990; Snyder et al., 1994) with annual sediment layers spanning the last *c*. 2000 years (Lapointe et al., 2019). In a first test run we targeted samples from the last *c*. 60 years (every cm, n = 23) with close to annual resolution to test if the sediments contain sufficient leaf wax concentrations for further analyses.

The sediment cores were subsampled at University of Copenhagen (Heftyevatnet) and University of Massachusetts Amherst (Linnévatnet), and the leaf wax extraction and analyses were performed in the Organic and Stable Isotope Biogeochemistry Laboratory at University at Buffalo. For details on the methods, see Schomacker and Kjellman (2021) and Kjellman (2022). In short, the leaf waxes were extracted from the sediments, quantified using gas chromatography (Heftyevatnet and Linnévatnet), and their hydrogen isotopic composition measured on a mass spectrometer (Heftyevatnet). We measured δ^2H_{wax} for chain lengths between C_{20} and C_{30} but focus our interpretations on the C_{28} and C_{22}, reflecting terrestrial and aquatic source water respectively. For Heftyevatnet, we calculated $\varepsilon_{28–22}$ to infer changes in summer evapotranspiration of terrestrial plants. We can do this because in this lake, (1) the source water for terrestrial and aquatic plants reflects the same precipitation seasonality, (2) we assume that aquatic source water does not experience evaporative enrichment, whereas terrestrial source water does, and 3) the terrestrial and aquatic waxes can be assumed to have similar apparent fractionation (Kahmen et al., 2013; Rach et al., 2017; Thomas et al., 2020). The leaf wax data were analyzed using the GeoChronR package (v. 1.1.10; McKay et al., 2021) in R (v. 4.2.2; R Core Team, 2022) to incorporate age uncertainty.

Preliminary results

The two aims of PPS2 were (1) to increase the temporal resolution, and (2) to increase the spatial resolution of leaf wax hydrogen isotope records from Svalbard. Ultimately, we increased the temporal resolution for Heftyevatnet (analyzed in PPS) and added one new high-resolution record from Linnévatnet. Due to delays related to the COVID-19 pandemic (preventing a planned 4-month research stay for Kjellman in Buffalo) and instrumental issues in the lab, we did not perform as many analyses as applied for (n = 50). Moreover, we decided to cancel some of the planned analyses based on the quality of the samples. The leaf wax concentrations in the Heftyevatnet core were so low that we decided to select a smaller number of samples (n = 6) from parts of the record with lowest resolution of samples and with high enough leaf wax concentrations. We expected similar problems for Linnévatnet since those sediments have low organic content and presumably also low concentrations of leaf waxes, and therefore focused on a rather small number of samples (n = 23), to test if the method works on sediments from this lake.

Heftyevatnet

The six samples analyzed in PPS2 showed δ^2H_{terr} and δ^2H_{aq} values within the range of the isotope values measured in PPS (Schomacker & Kjellman, 2021). The main difference was during the last *c*. 2.7 thousand years, where four samples were added, and the temporal resolution was improved from an average of 450 to 270 years between samples (Fig. 2). For some parts of the record (e.g., 9-7 cal. kyr BP, 4.5-2.7 cal. kyr BP), the resolution remains low (sometimes >500 years between samples), because the biomarker concentrations were too low for reliable measurements.

Both the terrestrial and aquatic leaf waxes from Heftyevatnet were interpreted to reflect summer precipitation isotopes (Fig. 2A-B), and $\varepsilon_{28–22}$ to reflect summer evaporative enrichment (Fig. 2C). Relatively stable δ^2H_{terr} and δ^2H_{aq} in the beginning of the Early Holocene suggested relatively stable summer conditions, followed by drier climate and more evapotranspiration after *c*. 9.3 cal. kyr BP, as indicated by increasing δ^2H_{terr} and higher $\varepsilon_{28–22}$. The summers likely

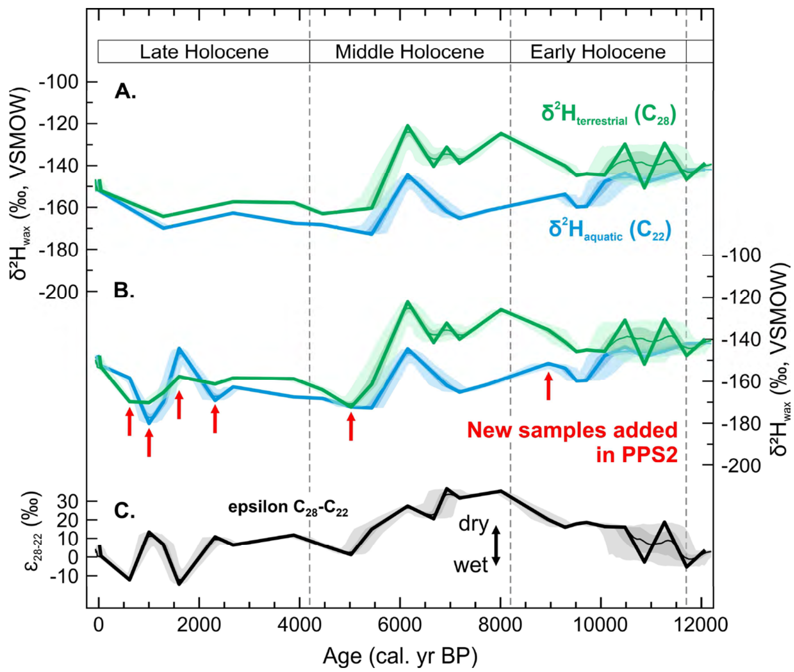

Fig. 2. Leaf wax hydrogen isotopic composition (δ^2H_{wax}) for C_{22} (blue, aquatic) and C_{28} (green, terrestrial) fatty acids from Heftyevatnet. Data generated as part of PPS (A) and including new data from PPS2 (B). Red arrows indicate samples added in PPS2. (C) ε_{28-22} (the difference between δ^2H of C_{28} and C_{22}), used to infer changes in evapotranspiration of terrestrial plants.

remained dry until *c*. 6 cal. kyr BP, after which decreasing δ^2H_{terr}, δ^2H_{aq}, and ε_{28-22} indicated a trend towards cooler and wetter summers with less evapotranspiration. When adding the new samples, both the terrestrial and aquatic isotope values displayed larger amplitude variability the last *c*. 2.7 thousand years (Fig. 2B). This might indicate that the Late Holocene climate was more dynamic than the original, lower resolution record suggested (Fig 2A).

Linnévatnet

The leaf waxes from Linnévatnet were quantified but are yet to be measured for their isotopic composition. The lipid concentrations were low throughout the record, with slightly higher values in the top (Fig. 3). Due to the low amounts of waxes in the samples, we must take some extra measures to get reliable isotope measurements. Rather than aiming to inject high enough concentrations of all chain lengths (C_{20} to C_{30}), we will optimize the output for one chain length. Since the leaf waxes in this lake are likely predominately of terrestrial origin, we will focus on one of the longer chain lengths (e.g., C_{26} or C_{28}). If successful, the next step is to analyze samples covering the entire instrumental record (the last *c*. 120 years) at high resolution (1-10 years per sample) and lower resolution (every *c*. 50 year) the last *c*. 2000 years. This high-resolution record will allow us to explore how well the δ^2H_{wax} values correlate to seasonal precipitation variability.

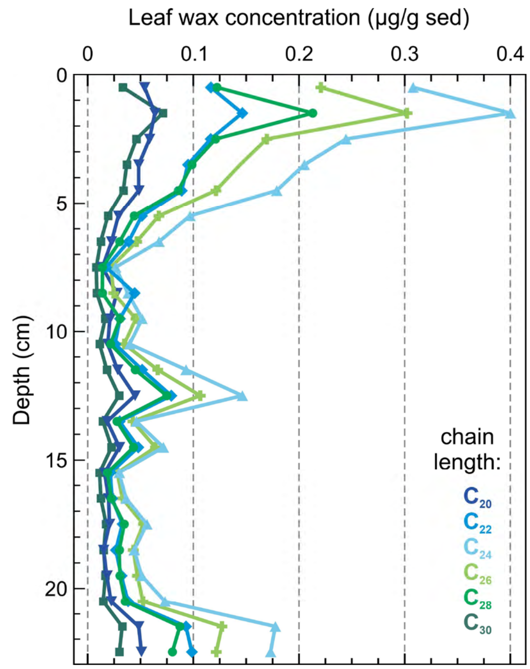

Fig. 3. Leaf wax concentrations for C_{20} to C_{30} fatty acids from 0.5-23.5 cm depth (the last *c*. 60 years) in the Linnévatnet sediment core.

Summary

Past Precipitation on Svalbard 2 has provided a valuable contribution to our growing leaf wax isotope dataset and increased understanding of past precipitation variability on Svalbard. The Heftyevatnet data generated in PPS2 will be presented in a manuscript together with data from PPS. This manuscript presents data from four lakes across Svalbard to explore regional differences in Holocene water cycle changes. We discuss summer precipitation changes across Svalbard as well as changes in the seasonal distribution of precipitation on northern Svalbard. Some of the main findings are that summer precipitation variability follows changes in insolation and temperature, whereas regional surface ocean conditions (e.g., inflow of warm Atlantic water, and reduction of sea ice) control the seasonal distribution of precipitation. This manuscript is soon ready to be published.

The work on the Linnévatnet samples will be continued, by finalizing the analyses of the already extracted and quantified samples, as well as extending the record further back in time. These data will be written up into a separate manuscript, focusing on comparing δ^2H_{wax} to precipitation measurements from Isfjord Radio. By generating a high-resolution δ^2H_{wax} record covering the instrumental period, we will evaluate how well δ^2H_{wax} correlates to seasonal (summer) precipitation variability.

Dissemination of project results (PPS and PPS2)

Scientific publications

Kjellman, S. E., 2022. Holocene precipitation seasonality on Svalbard and in Northern Fennoscandia reconstructed using organic geochemical and stable isotope proxies. Doctoral thesis, UiT The Arctic University of Norway, 188 pp. Disputation date: 23.09.2022. https://hdl.handle.net/10037/26641.

Kjellman, S. E., Schomacker, A., Thomas, E. K., Håkansson, L., Duboscq, S., Cluett, A. A., Farnsworth, W. R., Allaart, L., Cowling, O. C., McKay, N. P., Brynjólfsson, S., & Ingólfsson, Ó., 2020. Holocene precipitation seasonality in northern Svalbard: Influence of sea ice and regional ocean surface conditions. *Quaternary Science Reviews 240*, 106388, 1-15. https://doi.org/10.1016/j.quascirev.2020.106388.

Scientific presentations

Kjellman, S. E., Thomas, E. K., Schomacker, A., Farnsworth, W. R., Cowling, O. C., Allaart, L., Brynjólfsson, S., 2022. Seasonal distribution of precipitation on Svalbard modulated by regional ocean surface conditions and sea ice during the Holocene. IAL IPA Joint Meeting, Bariloche, Argentina. *Presentation*.

Kjellman, S. E., Thomas, E. K., Schomacker, A., Farnsworth, W. R., Cowling, O. C., Allaart, L., Brynjólfsson, S., 2022 Holocene precipitation seasonality along a climatic gradient from western Spitsbergen to Nordaustlandet, Svalbard. The 35th Nordic Geological Winter Meeting 2022, Reykjavík, Iceland. *Presentation*.

Kjellman, S. E., 2020. Holocene precipitation seasonality in Svalbard inferred from δ^2H of sedimentary leaf waxes. CHESS Annual Meeting 2020, Tromsø, Norway. *Presentation.*

Kjellman, S. E., Schomacker, A., Thomas, E. K., Håkansson, L., Duboscq, S. M., Cluett, A., Farnsworth, W. R., Allaart, L., & Cowling, O., 2019. Leaf wax hydrogen isotope reconstruction of Holocene precipitation seasonality in High Arctic Svalbard. 49th International Arctic Workshop, Stockholm, Sweden. *Presentation.*

Kjellman, S. E., Schomacker, A., Håkansson, L., & Thomas, E. K., 2018. Holocene Arctic precipitation and its response to sea ice extent – using leaf wax hydrogen isotopes as a proxy. IPA-IAL Joint Meeting, Stockholm, Sweden. *Poster.*

Popular scientific communication

Kjellman, S. E., 2021. Geological theme night for students, UiT Faculty of Science and Technology, Tromsø. 'Hvordan kan vi bruke arktiske innsjøsedimenter for å rekonstruere tidligere miljøer og klima? - Hydrogenisotoper i bladvoks og andre proxies'. *Presentation (in Norwegian).*

Kjellman, S. E., 2020. Formidlingskonkurransen 2020. Geoforskning.no. Hydrogenisotopenes hemmelighet. https://geoforskning.no/hydrogenisotopenes-hemmelighet/ *Popular scientific article (in Norwegian).*

Kjellman, S. E., 2019. Science for schools, Arctic Frontiers 2019. Nordnorsk vitensenter, Tromsø. "Arktiske innsjøer som klimaarkiver - Hva kan gjørme og bladvoks fortelle om tidligere klima på Svalbard?". *Presentation (in Norwegian).*

Work in progress

Kjellman, S. E., Thomas, E. K., Schomacker, A., Farnsworth, W. R., Cowling, O. C., Allaart, L., & Brynjólfsson, S. (in prep) Holocene precipitation seasonality along a climatic gradient from western Spitsbergen to Nordaustlandet, Svalbard (working title). Expected publication 2023.

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